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Forecasting models to quantify three anthropogenic stresses on coral reefs from marine recreation: Anchor damage, diver contact and copper emission from antifouling paint

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Abstract

This research focuses on damage to coral reefs from three anthropogenic stresses: the dropping of anchors and their chains, human contact, and emission of copper from antifouling paints. Forecasting models are described that quantify degradation in terms of percentage of coral cover damaged/year or increasing levels of water toxicity/year. The models utilize a Monte Carlo simulation that applies a range of values or a probability distribution to each of the numerous uncertain variables. This model has the flexibility to adapt, and become more accurate, when users input assumptions specific to their diving sites. Given our specific assumptions for a frequently visited site, anchors and their chains forecast a distribution of coral reef cover damage with a mean of 7.11% ± 4.77%, diver contact forecast a distribution of coral reef cover damage with a mean of 0.67% ± 0.38%, and antifouling paint forecast a distribution of copper level increase in the water with a mean of 0.037 ± 0.014 ppb. The results support recommendations for the implementation and sustained use of several specific marine recreation practices.

Keywords: Coral reefs; Marine recreation; Tourism; Diver damage; Anchors; Antifouling paint

1. Introduction

Coral reefs face natural and anthropogenic stresses. It is neither practical nor cost-effective for humans to protect coral reefs from natural stresses such as hurricanes (typhoons), extratropical storms, extreme rainfall and succeeding sediment runoff, intense long-period waves, tsunamis, or other natural events (Dollar and Grigg, 2004). However, there are many anthropogenic impacts that can and should be addressed. Those related to tourism, in particular, are often readily manageable and cost-effective.

This paper focuses on three of the most common impacts associated with marine recreation. The growth in mass tourism to coral reef destinations has been, and continues to be, robust. For example, an estimated 14 million people engage in SCUBA diving every year (Shackley, 1998). Many of these divers seek out coral reef ecosystems (Shackley, 1998). This paper examines some of the stresses to coral reefs by marine recreation providers and SCUBA divers and offers forecasting models that can be used to quantify ranges of damage caused by these marine recreation participants.

The models herein were influenced by previously published models (Hawkins and Roberts, 1992a,b, 1996; Dixon et al., 1993; McManus et al., 1997; Jameson et al., 1999). The models discussed here are similar to the previous models because the accuracies of all these models depend on, and are sensitive to, the validity of the assumptions made regarding the models' inputs. Our models distinguish themselves because of the software's

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ability to calculate and record so many different scenarios, as well as their ability to narrow their focus beyond the marine recreation sector in order to extract results of damage from causes in isolation.

The goal of this paper is not to provide an exact, universally applicable estimate of damage caused to every reef where marine recreation takes place. Rather, this paper attempts to provide a framework to help quantify reef degradation over time that is difficult to measure with precision and, in some cases, difficult to see with the naked eye. The inherent logic in these models facilitates a shift from a short-term perspective of coral reef degradation to a long-term perspective to guide appropriate behavior. The long-term perspective is critical to the implementation of best management practices because it aggregates the miniscule damages of the short-term into substantial damages evolving over time. It is intuitively clear that dropping anchors and their chains on reefs, damaging reefs through actual human contact, and emitting toxic substances into the waters above reefs from antifouling paints is detrimental to reefs in the short- and long-term. The models provided verify this intuition and support the argument for the implementation of affordable and sustainable best management practices for the marine recreation sector.

2. Methods

2.1. Methodology

Three main steps were used in the process of building these models. First, specific damages to coral reefs from marine recreation were identified. Damage from anchors and from human contact with coral reefs while SCUBA diving were chosen because the damage they inflict is immediate and visible, as well as the fact that these two causes can be alleviated easily when marine recreation stakeholders use best practices. The damage caused by copper emissions from antifouling paint was chosen because its effects are not easily seen by the naked eye. In addition, the reasoning behind the quantification of damage caused by antifouling paints is an example of a thought process that can be used with regards to other causes of damage to coral reefs that are not easily seen, such as damage from the discharge of oil, untreated sewage and toxic cleaning products.

Second, individual models were created to quantify the impact of each cause in isolation (Hawkins and Roberts, 1992a,b, 1996; Dixon et al., 1993; McManus et al., 1997; Jameson et al., 1999). The aforementioned causes of damage are unique in their scope of impact not only because of particular characteristics of the causes, but also because of the distinctive interactions each cause has with the differing variables in the marine ecosystem that influence the intensity of the damages to coral reefs.

Third, assumptions were quantified and input into the models. Some assumptions were founded on published research by field experts, while other assumptions were based on interviews with Joe Schittone, Marine Ecologist, National Oceanic & Atmospheric Administration, Anthony Rouphael, URS Corporation, Australia (regarding some of the parameters relating to diving in the Great Barrier Reef region), and Rich Wilson, Outreach Coordinator, The Coral Reef Alliance. Responses recorded in the interviews were, at the sole discretion of the authors, averaged with specific weightings. For simplicity, the source of these assumptions is referenced as "interviews" in Sections 2.2.1, 2.2.2 and 2.2.3.

2.2. Quantitative models

The three forecasting models provided are only as accurate as the assumptions they are based upon. The fact that the models' results are sensitive to the accuracy of each and every assumption included cannot be overemphasized, because all assumptions are direct components of the equation from which all outputs are derived. Numerous assumptions are defined as ranges of possibilities. As the ranges of assumptions narrow, the resulting distribution of damage decreases in breadth. Moreover, a goal of this paper is to provide those involved in marine activities with a model into which singular, finite figures can be input for a particular coral reef area so the resulting damage is a single percentage or level, as opposed to the range of damages provided here. For example, if a marine park manager observes a diving site and records his/her best estimate of the size of the site, the percentage of coral cover, how many vessels drop anchors, how often the anchors land on coral cover, and the area of damage of each event, then these inputs will allow the model to provide a finite percentage of damage. The models discussed here illustrate a logical procession and will be most useful when site-specific data replace the current generalized assumptions.

The models perform Monte Carlo simulations with Crystal Ball software, a Microsoft Excel add-in. The simulations provide the means to rapidly generate and analyze copious possible results of the models by applying a range of values or a probability distribution to each uncertain variable. The software generates random values from within the defined probability ranges, and then recalculates the model one million times, storing the results of each individual, hypothetical scenario. This timesaving process alleviates having to manually enter different scenarios over and over again.[1]

[1] http://www.decisioneering.com/crystal_ball/info_index.html. Examples of other environmental papers and articles using this software can be found at: http://www.decisioneering.com/environ/papers.html.

The models exhibit, in columns from left to right, a code to reference the variable in succeeding equations, a verbal description of this same component, a numerical representation of the description (either as a finite figure or as a distribution), and the equation or a narrative of the distribution that creates the numerical representation. The numerical representations in Tables 1–3 are examples of one of the one million scenarios calculated and recorded during this research. Several equations are not shown in the tables that keep the outcomes in the realm of possibility; e.g., "if, then" equations are used to keep results from going above 100%. The rationales and/or sources upon which specific assumptions are based are discussed individually in Sections 2.2.1, 2.2.2 and 2.2.3.

2.2.1. Anchor and anchor chain

The anchor and anchor chain model (Table 1) quantifies the percentage of coral cover that is damaged, either through coral fragments being broken off or from tissue abrasion, in one year from boat anchors being dropped onto reefs to hold boats in place (Williams, 1988; McManus et al., 1997; Creed and Filho, 1999; Rogers and Garrison, 2001; Dinsdale and Harriott, 2004). Williams (1988) and Creed and Filho (1999) discussed damage by anchors to seagrass. Rogers and Garrison (2001), among others, documented damage caused by the anchor of a cruise ship. McManus et al. (1997) described anchor damage caused by fishermen. This is the first model to quantify the percentage of coral cover damaged by both anchors and also their chains dropped by marine recreation providers.

The following is a discussion of the rationale for the inclusion of the assumptions in the model, provided by code (in parentheses; see Table 1). (A_1) The number of times boats visit the example dive site each day was based on interviews. In calculating estimates, respondents recognized that while some divers buy packages of dives, operators rarely take divers to the same site on the same day and have preferred sites. The model is quite sensitive to this input and the percentage of damage caused by anchors increases proportionately with the number of boats that visit the site. (A_2) The surface area of the dive site of 90,000 m^2 on which an anchor could be dropped is based on interviews. An important implicit assumption here is that the operator always drops an anchor, as opposed to mooring to a buoy or drifting. (A_3) Coral cover of 26% was documented by a 3-year research project that observed 20 coral reefs in the Atlantic Ocean (Carlson, 2003). By using percentages rather than absolute numbers we factor out the potential confounding effects/differences in coral cover which exist among sites (Hawkins and Roberts, 1996). (A_5) The area of damage caused by each anchor that hits coral, 0.16 m^2, is the area of destroyed seagrass measured and documented by Creed and Filho (1999) and Williams (1988). The model is sensitive to this input, and it is recognized that this input could be larger or smaller than the area assumed here because there are a variety of shapes and sizes of anchors in use and coral reefs have different physical compositions than seagrass. (A_6) The normal distribution (mean of 13% ± 1 SD of 1%) of time that the boat anchor lands—intentionally or unintentionally—on healthy coral, as opposed to non-coral substratum or already damaged coral, was derived from interviews. (A_8) The normal distribution (mean of 300 ± 1 SD of 25) of days per year that boats travel to the site because these days do not have excessive wind, rain, cloudy underwater visibility, any other restricting weather condition, and/or lack of tourists was based on interviews. (A_{11}) The average length of the anchor chain is a distribution of the

Table 1
Anchor and chain damage model

Code	Verbal description of variable	Numerical representation	Equation
A_1	Total number of anchor drops (boat trips) per day at site	**2**	Custom distribution: 20% = 1, 60% = 2, 20% = 3
A_2	Total area of dive boat operating (m^2)	90,000	300 m × 300 m
A_3	Coral cover on reef slope (%)	26%	26%
A_4	Coral cover in dive boat operating area (m^2)	23,400	$A_2 \times A_3$
A_5	Area of substratum contacted/damaged per drop (m^2)	0.16	0.16 m^2
A_6	Percentage of time anchor lands on coral	**14%**	Normal distribution: mean of 13%, SD of 1%
A_7	Area of coral damaged per drop (m^2)	0.137	$A_5 \times A_6$
A_8	Good days (weather and tourists permit boating) per year	**238**	Normal distribution: mean of 300, SD of 25
A_9	Area of coral damaged per year (m^2)	65.20	$A_1 \times A_7 \times A_8$
A_{10}	Corals damaged each year from anchors (%)	0.28%	A_9/A_4
		0.28%	
A_{11}	Chain length (m)	**5**	Custom distribution: 25% = 3, 50% = 5, 25% = 7
A_{12}	Amount of time boat is anchored (h)	**1.54**	Normal distribution: mean of 1.5, SD of 0.25
A_{13}	Area of chain damage per drop (m^2)	10.06	$((A_{12}/(12\ h)) \times Pi \times A_{11}^2)$
A_{14}	Area of coral damage from chain per drop (m^2)	2.62	$A_{13} \times A_3$
A_{15}	Corals damaged each year from anchor chains (%)	5.32%	$(A_1 \times A_8 \times A_{14})/A_4$
A_{16}	Total corals damaged each year from anchor and chain (%)	**5.60%**	$A_{10} + A_{15}$

approximate lengths of three of the most common chain lengths for small boats. (A_{12}) The normal distribution (mean of 1 h and 30 min ± 1 SD of 7.5 min) of time a boat is anchored at a dive site was based on interviews. (A_{13}) The area of coral that is damaged by chain during each anchoring episode assumes that the anchor is stationary and the chain will sweep through the area of a circle in approximately half a days time because in 12 h the tides have reached both a temporary zenith and also nadir. The other components of the models are equations that use the aforementioned assumptions to quantify the area of coral that is damaged each year and the area of the coral cover.

2.2.2. Human contact

The human-diver-contact model (Table 2) quantifies the percentage of coral cover that is damaged, either through coral fragments being broken off or from tissue abrasion, in one year. This model is different from other site specific research (Liddle and Kay, 1987; Kay and Liddle, 1989; Talge, 1992; Hawkins and Roberts, 1992a,b, 1993, 1996; Dixon et al., 1993; Prior et al., 1995; McManus et al., 1997; Medio et al., 1997; Rouphael and Inglis, 1997; Shackley, 1998; Hawkins et al., 1999; Jameson et al., 1999; Plathong et al., 2000; Townsend, 2000; Tratalos and Austin, 2001; Zakai and Chadwick-Furman, 2002; Dollar and Grigg, 2004) because no field observations were made by the authors. Instead, aggregations and weighted averages of documented field observations of others were used to create this model. Unlike previous models, this model allows coral reef stakeholders to input figures specific to their site, such as the number of divers from a dive operator's log book, in order to make the model their own. In addition, this model isolates human contact from the broader anthropogenic stresses, ranging from sunscreen penetrating a coral reef ecosystem to anchor damage, which can define the carrying capacity of a site.

The following is a discussion of the rationale for the inclusion of the assumptions in the model, provided by code (in parentheses; see Table 2). (A_{18}) The number of divers on each boat trip to each diving site each day is a custom distribution with a minimum of 6, a maximum of 20 and a median of 12 and was based on interviews. (A_{19}) The normal distribution (mean of 45 min ± 1 SD of 7.5 min) of a typical dive length was based on interviews. (A_{20}) The number of human contacts with coral reef of 0.11 per minute was calculated from an average of the observation and documentation by Medio et al. (1997), Prior et al. (1995), Rouphael and

Table 2
Diver contact damage model

Code	Verbal description of variable	Numerical representation	Equation
A_{17}	Boat trips bringing divers per day	2	A_1
A_{18}	Divers per boat per day	**10**	Custom distribution: 6 min, mean 12, max. 20
A_{19}	Typical dive length in minutes	**50.72**	Normal distribution: mean 45 min, SD of 7.5 min
A_{20}	Weighted average corals contacted per minute	0.11	$(0.9/7 \times 3360/9403) + (0.635/5 \times 1543/9403) + (0.45/10 \times 1500/9403) + (5/45 \times 1500/9403) + (6.56/45 \times 1500/9403)$
A_{21}	Potentially harmful contacts per day	117	$A_{17} \times A_{18} \times A_{19} \times A_{20}$
A_{22}	% of all contacts that break or damage coral	20%	20%
A_{23}	Damage done by each contact (m^2)	**0.0145**	Custom distribution: 50% = .0145 m^2, 50% = .027 m^2
A_{24}	Good days per year	**238**	A_8
A_{25}	Coral cover in dive area (m^2)	23,400	A_4
A_{26}	Corals damaged each year (%)	**0.00%**	$(A_{21} \times A_{22} \times A_{23} \times A_{24})/A_{25}$

Table 3
Copper level increase from antifouling bottom paint model

Code	Verbal description of variable	Numerical representation	Equation
A_{27}	Surface area = length × beam × 0.85 (m^2)	20.8845	$9.1 \times 2.7 \times 0.85$
A_{28}	Passive leaching (Ug/cm^2/day) modified epoxy	**4.15**	Normal distribution: mean of 4.32, SD of 0.26
A_{29}	Hull cleaning (Ug/cm^2/event) modified epoxy	**19.09**	Normal distribution: mean of 17.45, SD of 0.825
A_{30}	Annual dissolved copper mass emissions in grams	318.47	$(A_{27} \times A_{28} \times 365 \times 10{,}000/1{,}000{,}000) + (A_{29} \times 13 \times 10{,}000/1{,}000{,}000)$
A_{31}	Total dive area (m^3)	900,000	$A_2 \times 10$ m
A_{32}	Ocean water density in g/m^3	1,027,000	(1027 kg/m^3) × 1000
A_{33}	Total billions of grams of seawater in dive area	924.3	$(A_{31} \times A_{32})/1{,}000{,}000{,}000$
A_{34}	Annual increase in copper ppb from one boat's emissions	0.34	A_{30}/A_{33}
A_{35}	Annual increase in copper ppb from boat traffic above dive site	**0.029**	$A_{34} \times A_1 \times A_{12}/24 \times A_8/365$

Inglis (1997), Talge (1992) and Townsend (2000), weighted by minutes of diver observation (estimated at 1500 min for Talge and Townsend). (A_{22}) The assumption that 20% of all diver contacts break off coral reef fragments or abrade tissue was derived from interviews. (A_{23}) The area of damage done by each harmful contact is a custom distribution (50% probability of .0145 m^2 and a 50% probability of .027 m^2) founded on the research of Talge (1992).

2.2.3. Copper emission from antifouling paint

The antifouling paint model (Table 3) quantifies the annual increase in copper, measured in parts per billion (ppb), that is emitted from boats into seawater at a diving site (Marshall et al., 2002; Negri et al., 2002; Shimek, 2002; Young, 2003; Schiff et al., 2004). This model provides a unique perspective because it combines the research on rates at which copper leaches from boat bottoms with the research on copper's effect on coral reef reproduction, in order to quantify the impact boat operators cannot see, but are nonetheless causing in the water underneath them. The following is a discussion of the rationale for the inclusion of the assumptions in the model, provided by code (in parentheses; see Table 3). (A_{27}) The surface area of the bottom of a boat of 20.89 m^2 and the distributions of copper leaching rates, (A_{28}) and (A_{29}), are from a technical report by Schiff et al. (2004). (A_{29}) This figure assumes the hull is not being cleaned with best practices (cleaning with the softest cloths, etc.). Schiff et al.'s (2004) distribution if best management practices are implemented would have a mean of 8.57 Ug/cm^2/event ± 1 SD of 0.35 Ug/cm^2/event. (A_{30}) Schiff et al. (2004) assumed a hull cleaning every 4 weeks and this figure is multiplied by 13 to annualize. This equation also converts square centimeters to square meters and micrograms to grams. (A_{32}) 1027 kg/m^3 is the density of average surface seawater listed by the website of the University Corporation for Atmospheric Research. This figure will increase, (become denser), if the depth increases and/or the water temperature decreases.

3. Results

3.1. Damage from anchors and anchor chains

Fig. 1 is a graphical representation of the range of results of running the anchor simulation model one million times. The mean of this range is 7.11% damage to coral cover in one year with one standard deviation of 4.77%. The minimum is 0.38% damage and the maximum is 36.08% damage. Table 4 displays these same results of percentage of coral cover damaged, in 10 percentile increments. Here it is visible that 10% of the time there was less than 2.18% damage, 10% of the time there was greater than 13.80% damage and the remaining 80% of the scenarios fell in between.

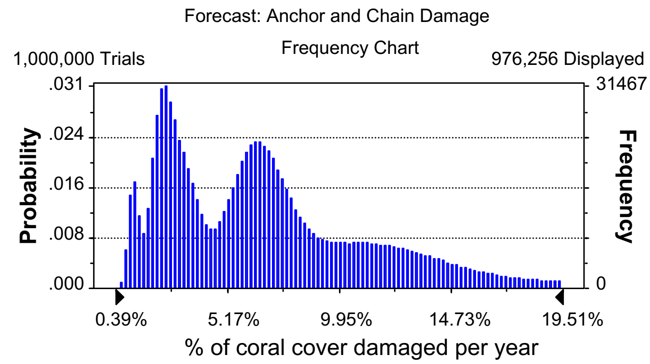

Fig. 1. Forecast of anchor and chain damage.

Table 4
Anchor and chain damage to coral cover

Percentile (%)	Percentage of coral cover damaged per year (%)
0	0.38
10	2.18
20	2.81
30	3.65
40	5.28
50	6.29
60	7.15
70	8.39
80	10.82
90	13.80
100	36.08

3.2. Damage from human contact

Fig. 2 is a graphical representation of the range of results of running the diver damage model. The mean of this range is 0.67% with one standard deviation of 0.38%. The minimum is 0.05% damage and the maximum is 3.97% damage. A cumulative function in this figure showed that 83% of the time less than 1% damage

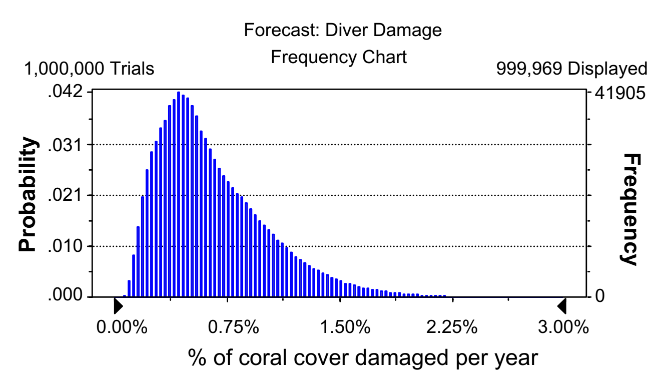

Fig. 2. Forecast of diver damage.

Table 5
Diver damage to coral cover

Percentile (%)	Percentage of coral cover damaged per year (%)
0	0.05
10	0.27
20	0.35
30	0.43
40	0.50
50	0.58
60	0.68
70	0.80
80	0.95
90	1.18
100	3.97

Table 6
Increase in copper level

Percentile (%)	Parts per billion per year
0	0.003
10	0.018
20	0.024
30	0.030
40	0.033
50	0.036
60	0.039
70	0.043
80	0.047
90	0.055
100	0.110

was recorded. Table 5 displays the percentage of coral cover damaged in 10 percentile increments. Table 5 shows that 10% of the time there was less than 0.27% damage, 10% of the time there was greater than 1.18% damage and the remaining 80% of the scenarios fell in between.

3.3. Damage from copper emission from antifouling bottom paints

Fig. 3 is a graphical representation of the range of results of running the copper level model. The two peaks are formed through the aggregation of results of the two normal distributions of copper emission rates, daily emission into the water and emission from hull cleaning, and look different than the lognormal-type result in Fig. 2. The mean of this range is an increase of 0.037 copper ppb with one standard deviation of 0.014 ppb. The minimum is an increase of 0.003 ppb and the maximum is an increase of 0.110. Table 6 displays the copper level increase in 10 percentile increments. This numerical representation appears more equally distributed around the mean of 0.037 ppb than Fig. 3.

4. Discussion and recommendations

The forecasting models analyzed in this paper are unique relative to other models of coral reef damage because of the application of Monte Carlo simulations. More importantly, the resulting quantifications provide unprecedented numerical support for a widespread change in the behavior of marine recreation stakeholders. The ease of extrapolating the quantified short-term results of these models into tangible long-term consequences allows us to clarify, magnify, and comprehend the impacts of poor environmental practices. Policy decision makers and resource managers, ranging from marine protected area managers to government officials, can benefit from this model, as the results derived from their site-specific inputs can provide quantitative support for actions that will most efficiently prioritize resource allocation in accordance with their conservation objectives.

4.1. Anchors and anchor chains

Anchors and their connected chains can dislodge coral colonies from the substrate; break live portions

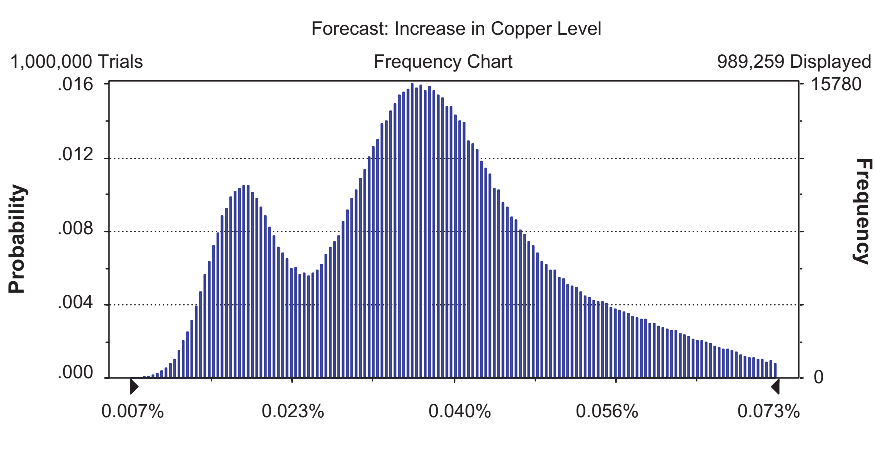

Fig. 3. Forecast of increase in copper level.

of a coral colony off into fragments—which often die and turn into rubble—leaving bright white round circles on the tops of individual branches of branching colonies; gouge out large pieces of tissue and skeleton (Dinsdale and Harriott, 2004); and cloud the surrounding water with disturbed sediment, which chokes corals and reduces the amount of sunlight that symbiotic algae require for photosynthesis (Pastorok and Bilyard, 1985). The anchor and anchor chain damage model reveals a direct relationship between increasing the number of anchors or the length of chains dropped on a dive site and the damage caused to the coral cover. Pulverizing the substratum with this anthropogenic stress is particularly detrimental because, given the slow growth rate for most coral species, it can take years, if ever, for coral colonies to recover (CORAL, 2004).

Fortunately, anchor damage can be easily prevented through the installation and use of mooring buoys, simple changes in boating habits and education. Mooring systems provide permanent lines that allow boaters to fix their position without dropping anchor, and boat operators can conserve coral reefs by using mooring buoys whenever possible. Where no moorings are present, diving boat operators may consider drift dives. If anchoring is absolutely necessary, boaters should make sure they are in designated areas away from important ecosystems and where they will not be dragged near these areas or accidentally cause damage (CORAL, 2004).

4.2. Human contact

SCUBA divers can damage coral reefs in ways quite similar to anchors, although usually on a much smaller individual scale. Divers crush and break corals and other reef dwelling organisms with fins, hands, equipment; and body parts, and stir sediment clouds with fins (CORAL, 2004). Zakai and Chadwick-Furman (2002) estimated that on a typical SCUBA dive of 60 min at 4–8 m depth, each recreational diver broke 1.7 ± 4.9 corals and raised 9.4 ± 11.9 sediment clouds onto the reef ($n = 251$ divers). Our model estimates a very similar amount of mean coral breakages for that length of dive, 1.32. Impacts are usually a result of individuals or groups trying to gain control, get a closer look or photograph, stand or walk in a shallow area, fight a current, or handle, touch and/or feed wildlife (CORAL, 2004).

Dixon et al. (1993) developed a model in Bonaire from which they suggested a threshold carrying capacity of 4000–6000 dives per site per year, above which diving caused a degradation to the structure of the coral community. Hawkins and Roberts (1996) estimated the overall capacity of a protected area or resort to support recreational diving to be 5000–6000 dives per site per year. Their model shows approximately 4% of coral colonies are damaged in one year at this rate of dives. Our model, which has an approximate mean of 6800 dives per site per year, supports the two previously mentioned models—even though the mean percentage of annual damage from human contact is slightly less than 1%—because the aggregate damage caused by all marine recreation stakeholders is near the level reprinted by Hawkins and Roberts' data. This damage increases exponentially when the number of dives increases dramatically, as seen in Hawkins and Roberts' model.

Healthy coral growth rates and the rate of natural recovery of damaged corals are not factored into this model or either of the other two models. One reason for these omissions is that different species of corals grow, and recover from damage, at different rates. More importantly, these models are illustrative descriptions of impacts in isolation. For example, if coral cover in an area is growing at 5% and the anthropogenic damage is 5%, then it will appear that the reef is not changing significantly. These models express the notion that this coral area would have grown 5% in the absence of anthropogenic stress, so the damage—regardless of visible impact—is still 5%, even though it looks like the coral cover has not changed.

Medio et al. (1997) and Townsend (2000) found that both voluntary and involuntary contacts with coral reefs decreased in dramatic and statistically significant fashions when educational briefings were performed before and during dives. Medio et al. (1997) documented post-briefing divers with mean coral contacts that were six times less than those without the educational briefing and Townsend (2000) recorded that divers attending briefings contacted corals over three times less than the control group of divers. In both studies the control groups had similar dive experience and dived in the same locations as the divers receiving the educational briefing. Townsend (2000) concluded that briefings are the best and most effective form of interpretation and education in a boat diving environment, as opposed to literature such as educational posters put up inside the boats. The findings above suggest that marine recreation providers can significantly reduce damage caused by SCUBA divers, and snorkelers, with pre-dive educational briefings which: (1) explain the sensitive nature of coral reef ecosystems and show pictures of the most at-risk local species, (2) conduct basic dive skill trainings such as buoyancy refreshers with inexperienced, out-of-practice, or non-regular divers, and (3) establish a "no contact" policy that can be supported by encouraging the use of flotation vests for inexperienced snorkelers and discouraging the use of gloves by divers.

4.3. Antifouling paint

Antifouling paints emit a substance, usually a toxic biocide, which prevents organisms in the water from attaching to the underside of a vessel. A foul vessel bottom is slower, uses more fuel and requires more labor than a clean bottom (Colvin, 2004). Marshall et al. (2002) and Negri et al. (2002), among others, have documented the devastating and incredibly visible damage that the biocide tributyl tin (TBT) causes to coral reefs. Fortunately, TBT has been banned in the United States, Australia and most of Western Europe for vessels under 83 feet in length. Copper, while banned in bottom paints in the Netherlands, is still prevalent as a toxic biocide in numerous antifouling paints. Although antifouling paints can contain any number of biocides and toxic elements, this model only describes the increase in copper levels.

The damage to coral reefs caused by elevated copper levels in surrounding ocean water is different to the immediate physical harm caused by anchors and humans. Elevated copper levels inhibit some coral larvae from developing into juvenile coral polyps, a critical process of reef renewal (Young, 2003). Reichelt-Brushett and Harrison (2000) performed a 5-hour study of *Goniastrea aspera* and recorded a fertilization rate of 93% ± 4.0% in water with 2 ppb of copper; however, successful fertilization was significantly reduced to 41% ± 7.1% at 20 ppb of copper. Shimek (2002) documented an inhibiting fertilization concentration of 17.4 ppb for *Acropora millepora* in a test that only ran four hours. Claire Bennett observed two hard corals in a control, or "clean," seawater with 2–3 ppb of copper as well as coral in water with 5 and 30 ppb of copper (Young, 2003). The level of copper had no impact on the total number of larvae produced, but at 5 ppb, 30% fewer larvae developed into juveniles, compared with larvae in clean seawater. At 30 ppb, the number was reduced by 70%. Furthermore, larvae that did successfully mature took much longer to do so in the copper-laced waters than in clean water.

The latter study allows a fascinating perspective in conjunction with the results of the model. Table 6 shows a mean increase of a seemingly miniscule 0.027 copper ppb. The inputs of the model assume, on average, only 2 boats go to the site approximately every 5 out of 6 days and only stay there for 1 h and 45 min. Given these assumptions, it can be argued that nearly 100 times more boat trips would need to be made in order to increase copper levels to a rate that would inhibit 30% of larvae development. The point here is that a combination of forces—such as boats with larger bottoms, boats using paints with higher leaching rates, and/or boats that stay at the site longer (e.g. live-aboards anchoring for the night) can combine to increase the copper in the water to a level that would inhibit some reproductive development. Copper levels are most severe in areas where the water is not consistently flushed, such as in lagoons and boat harbors. When current and water movement move copper out of a diving site, the copper does not disappear. Instead, the copper is transferred to an adjacent marine ecosystem. Furthermore, wet season storms can increase copper levels by stirring up copper-laden sediment.

More long-term studies of the effects of copper and other toxic elements in paints are needed to make generalized assessments of the damage caused to reefs. What is clear is that increasing copper levels do inhibit coral spawning and reproduction. A best boat operator practice is to use antifouling paint that does not contain biocides when possible, or otherwise use a paint that contains neither TBT nor copper.

5. Conclusion

The impact of anthropogenic stresses on coral reef ecosystems are site-specific because a plethora of dynamic influences are involved. While no site-specific studies can be guaranteed to be representative of reefs around the globe, broad and general inferences can be made about damage caused by humans. The models described above, and the research cited in this paper, strongly support the following notions: (1) anchors and their chains are so destructive to coral reefs that mooring buoys should be installed and used wherever possible; (2) no matter how high the diving experience level, humans make detrimental physical contact with coral reefs. This can be substantially alleviated by conducting pre-dive educational briefings; (3) the harm caused by the leaching of heavy metals from antifouling paints can be minimized by using paints free from TBT and copper; and (4) using 4-stroke engines that reduce fuel and hydrocarbon output, using bilge pillows that absorb fuels and oils, substituting toxic boat cleaning products that contain phosphates and ammonia with natural cleaners like vinegar, citric juices, borax and baking soda, and using sewage pumpout facilities when possible, or otherwise treating onboard sewage with biodegradable and non-toxic products. Not using these types of best practices leads to coral reef damage that is not always visible. Forecasting models can be used to quantify anthropogenic impacts in the short and long-term. The results are explicit advocates of education as the foundation of marine recreation sector best practices. As coral reef tourism continues to grow around the world, so does the need to manage and mitigate anthropogenic stresses.

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